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Effects of coping designs on stress distributions in zirconia crowns: Finite element analysis

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Abstract

The purpose of this study was to evaluate the effects of coping designs on the stress distributions in posterior zirconia crowns by non-linear three-dimensional finite element analysis. Three-dimensional finite element models of a mandibular right first molar with layers of veneering porcelain, zirconia coping, cement, and abutment tooth were designed by computer software (HyperWorks 10.0). Ten zirconia crowns with different designs were produced according to various shoulder positions and heights. The shoulders (1-mm width) exhibited incremental height increases of 1 mm, 2 mm, and 3 mm on the buccal, lingual, and proximal sides, respectively. An axial compressive dynamic load simulating the progressive load was applied until a stainless steel ball model (7 mm in diameter) deepened the veneer surface to 0.7 mm in depth. Loads were placed on the inner inclines of the mesiobuccal, distobuccal, and mesiolingual cusps. Residual maximum principal stresses (MPSs) at the veneer and coping under progressive loading were determined for each zirconia crown. Reinforcements with the shoulders on the buccal, lingual, and proximal axial walls resulted in lower MPSs in the veneering porcelain but higher MPSs in the zirconia coping. As the shoulder height increased, the tensile stresses decreased, while the compressive stresses increased in the veneering porcelains. It can be concluded that the shoulder height and position in the zirconia coping will affect the MPSs of the crown. Our findings conclusively reveal the critical role of the shoulder design of the coping in preventing veneer fracture on posterior zirconia restorations by reducing tensile stresses in veneering porcelain.

Keywords: Fracture, stress; Finite element analysis; Dental prosthesis design; Zirconium

1. Introduction

Dental materials have undergone considerable improvement, and a variety of new systems have become widely used. Currently, there are several dental ceramic materials available on the market, including glass ceramics and polycrystalline ceramics. Their use is advantageous not only due to their favorable optical properties but also due to their adequate clinical function, favorable mechanical properties, and longevity [1–4]. Among these ceramic systems, the mechanical properties of zirconia are the highest ever reported, resembling those of metals. It has been termed 'ceramic steel' [5].

Zirconia can exist in three crystallographic polymorphs depending on the temperature: monoclinic, tetragonal, and cubic. Its structure is monoclinic below 1170 °C, tetragonal between 1170 and 2370 °C, and cubic above 2370 °C and up to the melting point [3]. When the tetragonal phase transforms to the monoclinic phase on cooling, a volumetric change in the crystal (*circa* 4.5% volume increase) may lead to fracture [3]. To retain the tetragonal structure at room temperature, stabilizing oxides, such as CaO, MgO, CeO_2, or Y_2O_3, are alloyed with pure zirconia [3]. The transformation from the tetragonal (*t*) phase to the monoclinic (*m*) phase at room temperature is due to the application of an external stress on the zirconia

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surface accompanied by a volumetric change. This stress-induced unique phenomenon, known as a $t \rightarrow m$ transformation, arrests crack propagation by crystalline expansion, which seals the crack and leads to high fracture resistance [5,6].

Zirconia has been introduced to prosthodontic dentistry for the manufacture of fixed dental prostheses (FDPs) and implant abutments in combination with computer-aided design and computer-aided manufacturing (CAD/CAM) techniques. Increased demand for metal-free restorations in posterior areas has increased our focus on zirconia restorations because of its advantages in patient comfort and acceptance and excellent mechanical properties. In this system, the crown coping is fabricated from high-strength zirconia ceramic materials and is veneered with feldspathic porcelain. It has been speculated that cracks originate on the internal surfaces of all-ceramic crowns, leading us to believe that it reinforces the crowns with high-strength ceramic copings [7]. However, in several reports, the failure rate of the crowns replaced in posterior areas has been described to be 3% to 4% per year [8–12]. The chipping or delamination of the veneering porcelain in zirconia prostheses is a problematic issue in prosthodontic dentistry, occurring in as many as 25% of all cases [13–22]. Therefore, the restoration of a molar with this material remains controversial.

Clinical studies have demonstrated that cohesive failure of veneering porcelain on zirconia prostheses is related to several contributing factors: fatigue, overloading, residual stress in veneering porcelain, mismatch of coefficients of thermal expansion (CTE), poor wettability of veneering porcelain, improper porcelain-coping thickness ratio, flaws on the veneering porcelain, porosities, and poor framework design [3,23–27]. Clinical studies with modified coping designs in zirconia crowns reported promising results [28–34]. Brittle veneering porcelains were fractured under tensile loads because of its low tensile strength, even with high compressive strength. Therefore, the design concepts of those studies focused on decreasing tensile stresses in veneering porcelains by the supportive structures of zirconia copings: a high palatal shoulder [29], a palatal and midproximal shoulder [28], a 2.5-mm-high lingual and proximal shoulder [32], and a proximal and lingual shoulder [30,31,33,34]. However, these studies did not offer information on the influence of variations of shoulder positions and heights on fracture resistance of veneering porcelain. Moreover, little on the variation of shoulder heights and positions in stress distribution of zirconia crown models has been researched [24].

The present study aims to examine the stress distribution and localize the critical sites within posterior mandibular zirconia crowns in different coping designs under progressive loading using three-dimensional (3D) finite element analysis (FEA). We hypothesized that there are differences in the stress distributions of the veneering porcelain and zirconia coping with various shoulder positions and heights.

2. Materials and methods

2.1. Tooth, zirconia coping, veneering porcelain solid models generation

The 1.2-mm-deep and 8°-convergence-angle chamfer was prepared on a mandibular right first molar resin model (D85DP-500B.1, Nissin Dental, Kyoto, Japan) using a carbide bur (Komet H 356 RGE 103.031, Gebr. Brasseler GmbH, Lemgo, Germany). The carbide bur was affixed to a surveyor (F1, DeguDent GmbH, Kanau, Germany) to ensure a standardized preparation. The crowns were completed by digitizing the unprepared and prepared resin models using an optical scanner (Optical 3D Scanner Activity 101, smart optics Sensortechnik GmbH, Bochum, Germany).

The variations in the zirconia coping designs were as follows: 1-mm-wide shoulder had incremental height increases of 1 mm, 2 mm, and 3 mm on the buccal, and lingual and proximal sides (Fig. 1 and Table 1).

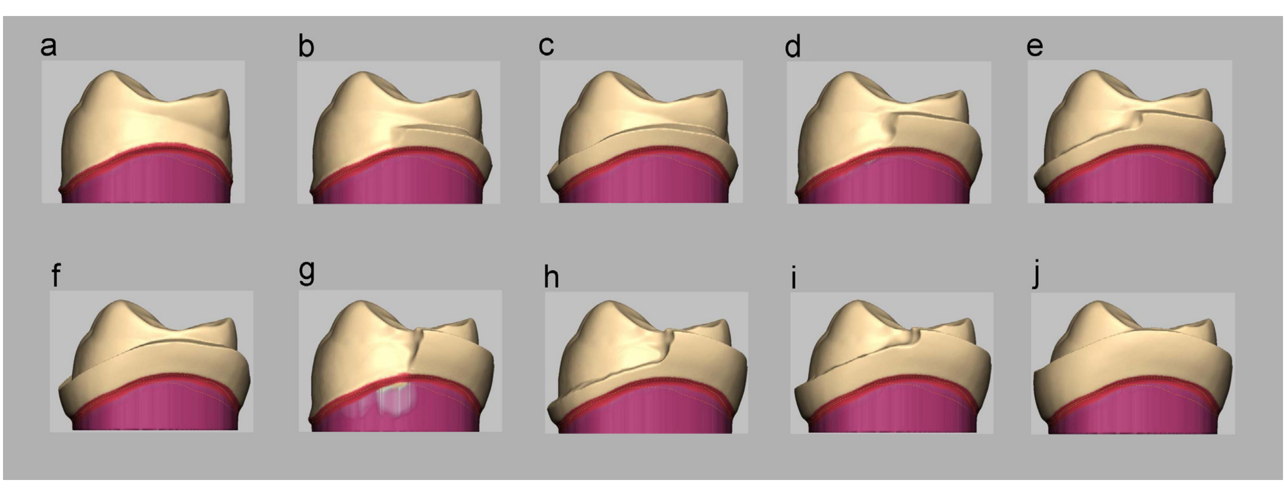

Fig. 1. Schematic image of the variations of shoulders in the zirconia coping designed in computer-aided design software. The 1-mm-wide shoulder variations in the copings were incremental increases of 1 mm, 2 mm, and 3 mm in the buccal (B) height and proximal and lingual (PL) height. (a) Model 1: no shoulder, (b) Model 2: PL 1 mm, (c) Model 3: PL 1 mm and B 1 mm, (d) Model 4: PL 2 mm, (e) Model 5: PL 2 mm and B 1 mm, (f) Model 6: PL 2 mm and B 2 mm, (g) Model 7: PL 3 mm, (h) Model 8: PL 3 mm and B 1 mm, (i) Model 9: PL 3 mm and B 2 mm, and (j) Model 10: PL 3 mm and B 3 mm.